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Supracrustal faults of the St. Lawrence rift system between Cap-Tourmente and Baie-Saint-Paul, Quebec[1]

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Abstract: The St. Lawrence rift system is made up of Late Proterozoic–Early Paleozoic supracrustal faults attributed to the opening of the Iapetus Ocean. The normal faults commonly occur at the contact between metamorphic rocks of the Grenvillian basement to the northwest and Cambrian–Ordovician strata of the St. Lawrence Lowlands to the southeast. Coastal sections of the St. Lawrence River that expose the Cap-Tourmente Fault and the St. Lawrence Fault have been studied between Cap-Tourmente and Baie-Saint-Paul. Fault rocks that mark these two normal faults consist of fault breccia, cataclasite, fault gouge, and pseudotachylyte. Field relations suggest that the various types of fault rocks are genetically related and associated to the same tectonic event. The comparison with faults characterizing the Charlevoix meteoritic structure indicates that brittle fault rocks are not limited to impact cratering, and that reactivation of the St. Lawrence rift system is a postimpact, probably Mesozoic phenomenon.

Résumé : Le rift du Saint-Laurent comprend des failles supracrustales du Protérozoïque tardif–Paléozoïque précoce qui sont attribuées à l'ouverture de l'océan Iapetus. Les failles normales se rencontrent généralement au contact des roches métamorphiques du socle grenvillien au nord-ouest et des strates cambro-ordoviciennes des basses terres du Saint-Laurent au sud-est. On a examiné des coupes sur la côte du Saint-Laurent entre Cap-Tourmente et Baie-Saint-Paul où sont exposées les failles de Cap-Tourmente et du Saint-Laurent. Les roches marquant ces failles normales comprennent de la brèche de faille, de la cataclasite, de la mylonite pulvérulente et de la pseudo-tachylite. Les relations de terrain font penser que ces différents types de roches sont associés génétiquement et issus d'un même événement tectonique. Une comparaison avec les failles qui caractérisent la structure météoritique de Charlevoix indiquent que les roches de failles cassantes ne sont pas formées uniquement par impact météoritique et que la réactivation du rift du Saint-Laurent s'est produite après l'impact, vraisemblablement au Mésozoïque.

[1] Contribution to the Appalachian Foreland and St. Lawrence Platform NATMAP Project.

INTRODUCTION

The St. Lawrence rift system is a seismically active zone (Adams and Basham, 1989) where fault reactivation is believed to occur along late Proterozoic to early Paleozoic normal faults related to the opening of Iapetus Ocean (Kumarapelli and Saul, 1966; St-Julien and Hubert, 1975; Kumarapelli, 1985). The rift-related faults fringe the contact between the Grenvillian basement to the northwest and Cambrian–Ordovician sedimentary rocks of the St. Lawrence Lowlands platform to the southeast, and occur also within the Grenvillian basement. The St. Lawrence rift system trends northeast and represents a half-graben that links the northwest-trending Ottawa–Bonnechère and Saguenay River grabens (Fig. 1A), both interpreted as Iapetan failed arms (Kumarapelli, 1985).

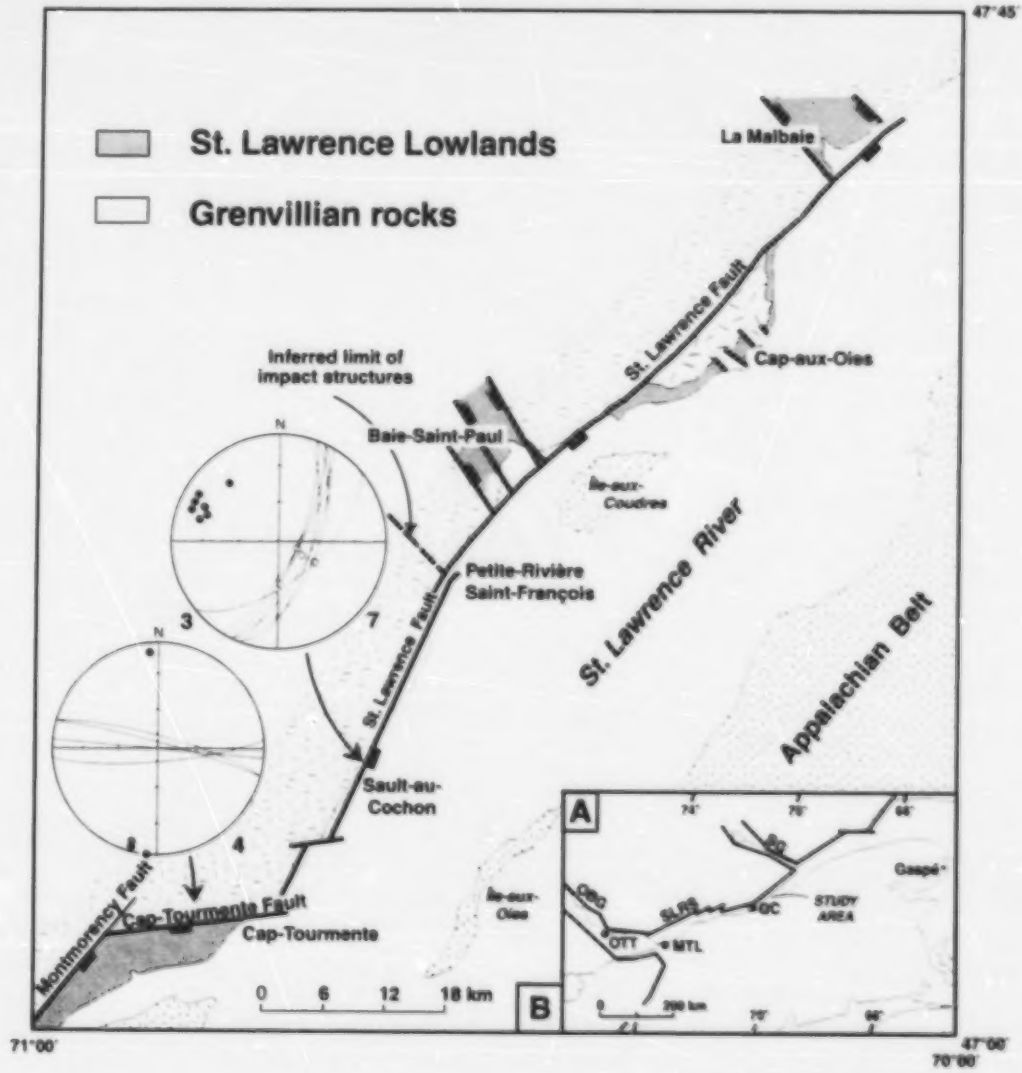

Figure 1. *A) Schematic map of the St. Lawrence rift system (SLRS) showing the location of the Ottawa-Bonnechère (OBG) and Saguenay River (SG) grabens (after Kumarapelli and Saull, 1966). OTT, Ottawa; MTL, Montréal; QC, Québec. B) Simplified geological map of the St. Lawrence rift system between Cap-Tourmente and La Malbaie. Stereographic projections show the orientation of fault fabrics and striations related to the St. Lawrence and the Cap-Tourmente faults in the study area. Numbers of measurements appear on the lower right (fault fabrics) and lower left (striations) of stereonets. Dashed line shows the inferred southern limit of impact structures according to Rondot (1989).*

Few field studies have been conducted on faults attributed to the St. Lawrence rift system. Lachapelle (1993) investigated some of these faults between Québec and Cap-Tourmente, and documented the occurrence of hydraulic fault breccia. He argued that fault orientations have been controlled by pre-existing basement structures, and that the occurrence of fault gouge along some of these structures mark the reactivation of rift structures during the Ordovician. Shaw (1993) reinterpreted faults of the St. Lawrence rift system in the Québec area and concluded that they represent a system of sinistral strike-slip faults formed during the early stage of the Appalachian compression. Rocher et al. (2000) conducted a regional-scale, paleostress analysis of supracrustal faults crosscutting and fringing the St. Lawrence Lowlands between Montréal and Québec. Although most faults are poorly exposed, cataclastic breccia and pseudotachylyte veins were recognized along several faults. Rocher et al. (2000) argued for a complex tectonic history involving faulting during Iapetus rifting, and reactivation during and after compressive deformation related to the Appalachian Orogen. Between Québec and the Saguenay River, Rondot (1968, 1971, 1989) identified a major normal fault within the Charlevoix impact crater, the St. Lawrence Fault, which he linked to similar faults southward and attributed to Iapetus rifting. More recently, Rondot (1998) stressed that fault breccia and pseudotachylyte dykes and veins found in the Charlevoix area are basically the result of impact cratering rather than representing inherited or neoformed faults. In order to discriminate between preimpact structures and syn- to postimpact faulting events, a structural study of supracrustal faults in the Charlevoix area has been initiated in 1999 as part of the GSC Appalachian Foreland and Platform Architectures in Québec, New Brunswick and Newfoundland NATMAP initiative of the Québec Geoscience Centre. Preliminary results (Lemieux et al., 2000) suggest that the relationships between structures related to impact cratering and structures left by the Iapetan rifting or younger faulting episodes are not obvious and need to be precisely determined.

For the present study, we have investigated supracrustal faults of the St. Lawrence rift system between Cap-Tourmente and Baie-Saint-Paul (Fig. 1B). Except for its northeastern extremity, the studied section is located well beyond the Charlevoix impact crater (Fig. 1B), and the exposed fault-related rocks and structures are therefore considered to be genetically related to the St. Lawrence rift system. In the following, we present the macroscopic characteristics of supracrustal faults of the studied area and a comparison to fault rocks of adjacent regions. The studied section offers excellent shoreline exposures along the St. Lawrence River and is easily accessible via a CN railroad that fringes the shoreline.

GEOLOGICAL SETTING

The studied section of the St. Lawrence rift system is located 50–80 km to the northeast of Québec, on the north shore of the St. Lawrence River (Fig. 1). The bedrock of the area essentially consists of Grenvillian metamorphic rocks made up of high-grade orthogneiss and paragneiss, charnockite, anorthosite, and granitoid intrusions of the Laurentides Park Complex (Sabourin, 1973; Laurin and Sharma, 1975; Rondot, 1989). Downfaulted Ordovician rocks of the St. Lawrence Lowlands platform are locally found to the south and southeast of the St. Lawrence rift system faults (Fig. 1B). The St. Lawrence Lowlands forms a slightly deformed Cambrian to Early Ordovician passive continental margin succession (Berstein, 1991) overlain by Middle to Late Ordovician shallow to deep, marine foreland basin deposits (Lavoie, 1994). In the Charlevoix area, Ordovician rocks unconformably overlie the Grenvillian basement on both sides of the St. Lawrence Fault (Rondot, 1989). To the northwest of the St. Lawrence Fault, rocks of the St. Lawrence Lowlands platform occur within two northwest-trending valleys interpreted as part of the impact-related annular graben (Rondot, 1989). The meteoritic origin of the Charlevoix structure has been established from abundant shatter cones, microscopic shock metamorphic features in breccia dykes and basement gneiss, and remnants of impact melt (Rondot, 1971, 1998; Robertson, 1975). The age of the crater is Devonian and has been established by K-Ar analyses ranging from 321 Ma to 372 Ma on the impact melt and breccia dykes (Rondot, 1971).

STRUCTURAL CHARACTERIZATION OF FAULTS

For the purpose of our study, we mapped brittle structures and fault rocks occurring along the shoreline of the St. Lawrence River from Cap-Tourmente to Baie-Saint-Paul, a distance of approximately 40 km (Fig. 1B). Two major supracrustal faults, known as the St. Lawrence and the Cap-Tourmente faults (Rondot, 1989), have been investigated. The two faults occur essentially within the Grenvillian crystalline basement. Remnants of the St. Lawrence Lowlands are only locally found, mainly along the Cap-Tourmente Fault (Fig. 1B). In the following section, we describe the orientation, the kinematics, and the nature of fault rocks related to both structures. For the textural classification of fault rocks, we used Sibson's (1977) classification as modified in Scholtz (1990); the only significant departure from the Sibson's classification being the addition of foliated gouge, which implies that both random- and foliated-fabric fault rocks can occur in the upper crustal, brittle frictional regime (see Snoke et al., 1998).

St. Lawrence Fault

The St. Lawrence Fault trends N020° to N050° and dips 60° to 70° toward the southeast (Fig. 1B, 2). It extends from Cap-Tourmente to Baie-Saint-Paul and is essentially parallel to the St. Lawrence River. Northward, the St. Lawrence Fault has been mapped by Rondot (1989) and crosses the Charlevoix crater without major trend deflection or fault offsets within or at the boundaries of the impact structure (Fig. 1B). In the study area, remnants of Ordovician rocks belonging to the St. Lawrence Lowlands occur in the hanging

Figure 2.

Panoramic view of the St. Lawrence Fault (SLF) at Sault-au-Cochon. Fault breccia and cataclasite are exposed along the shoreline at the base of the cliff. View toward the northeast.

wall of the St. Lawrence Fault at Petite-Rivière-St-François and at Sault-au-Cochon. The fault is superbly exposed along the coast approximately 1 km north of Cap-Tourmente and at Sault-au-Cochon (Fig. 2). The quality of the exposure at Sault-au-Cochon is exceptional and this locality can be considered as a type-section for the St. Lawrence Fault.

At Sault-au-Cochon, fault rocks related to the St. Lawrence Fault consist of fault breccia, fault rocks of the cataclasite series, foliated gouge, and pseudotachylyte (Fig. 3). During low tides, limestone and limy sandstone of the St. Lawrence Lowlands are exposed in the hanging wall of the fault, in contact with fault breccia zones developed in the metamorphic basement. The minimum true thickness of fault-related rocks exposed at Sault-au-Cochon is 20 m. Rock fragments in fault breccia are angular to subangular and vary from a few centimetres to more than 20 cm in diameter (Fig. 3A). The breccia matrix is made up of fine-grained rock fragments (i.e. the size of crush and fine crush breccia) and is commonly chlorite-rich. Quartz- and/or calcite-rich veinlets, similar to those described by Lachapelle (1993) and Carignan et al. (1997), are locally found. An ill-defined planar fabric, hosting downdip or steeply plunging striations (Fig. 1B), is frequently developed in fault breccia. This fabric is locally associated with nascent shear bands structures that indicate normal-sense faulting toward the southeast. Veinlets of dark-coloured pseudotachylyte (Fig. 3B) are common within the fault breccia and trend both parallel and at high angle with the dominant fabric of the fault. Pseudotachylyte is also locally found as a fine-grained component in the matrix of breccia. Decimetre-thick horizons of foliated ultracataclasite associated with fault gouge and foliated gouge are locally well exposed (Fig. 3C). Nascent C/S fabrics and shear bands are developed in the ultracataclasite and clearly indicate normal-sense faulting (Fig. 3C). The gouge horizon is characterized by visible fragments of basement rocks in a fine-grained matrix of rock powder (Fig. 3D). The contact between cataclastic rocks of the St. Lawrence Fault and unfaulted basement rocks is abrupt, but hosting rocks commonly show the progressive development of fractures trending parallel to the fault zone that are pervasively developed (more than 20 joints per metre) in metamorphic rocks adjacent to (i.e. within 5 m) the fault boundaries.

The segment of the St. Lawrence Fault exposed at Cap-Tourmente consists of 10–15 m thick zones of protocataclasite, cataclasite, and fault breccia of basement rocks. Brittle factures filled with dark pseudotachylyte, identical to those found at Sault-au-Cochon, are also found. At the Cap-Tourmente section, the St. Lawrence Fault clearly crosscuts east- to northwest-trending brittle faults that are interpreted as subsidiary structures to the Cap-Tourmente Fault.

Cap-Tourmente Fault

The Cap-Tourmente Fault trends east and dips approximately 80° to the south (Fig. 1B). The fault runs parallel to a huge cliff at the contact between the Grenvillian basement to the north and the St. Lawrence Lowlands to the south. Westward, it crosscuts or merges within the Montmorency Falls Fault, a St. Lawrence rift system fault exposed near Québec.

Fault rocks that marked the Cap-Tourmente Fault are identical to those of the St. Lawrence Fault, and mostly consist of fault breccia, cataclastic rocks, and dark pseudotachylyte veins (Fig. 3E, F). Fault breccia zones are more than 10 m thick, and are made up of centimetre- to decimetre-scale fragments of gneiss, granitoid rocks, and marble settled in a fine-grained matrix of crush breccia. Calcite cementation of the crush breccia matrix is locally observed. Fault striations were not observed. As for the St. Lawrence Fault, pseudotachylyte occurs as centimetre-wide veins or forms a composite matrix with fine-grained rock fragments (Fig. 3F). Minor faults trending approximately N120° and steeply dipping northeast or southwest occur in the footwall of the Cap-Tourmente Fault. These faults are marked by closely spaced, northwest-trending brittle fractures or by 50 cm to 1 m wide zones of cataclasite with pseudotachylyte veins. They are interpreted as Riedel-type secondary structures related to the Cap-Tourmente Fault. Along the St. Lawrence River, continuous exposure clearly shows that the northwest-trending faults are crosscut by northeast-trending fault zones related to the St. Lawrence Fault.

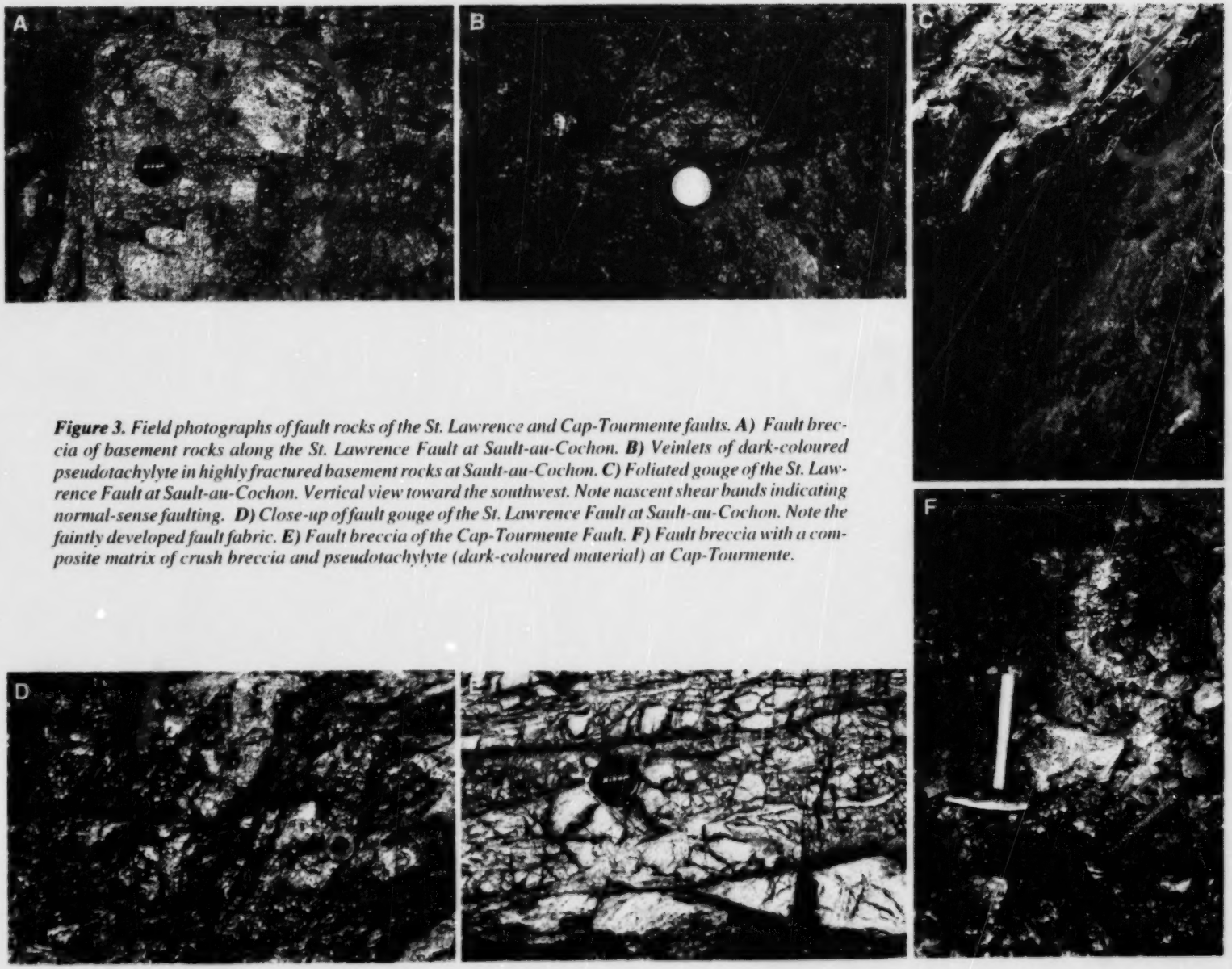

Figure 3. *Field photographs of fault rocks of the St. Lawrence and Cap-Tourmente faults.* ***A)*** *Fault breccia of basement rocks along the St. Lawrence Fault at Sault-au-Cochon.* ***B)*** *Veinlets of dark-coloured pseudotachylyte in highly fractured basement rocks at Sault-au-Cochon.* ***C)*** *Foliated gouge of the St. Lawrence Fault at Sault-au-Cochon. Vertical view toward the southwest. Note nascent shear bands indicating normal-sense faulting.* ***D)*** *Close-up of fault gouge of the St. Lawrence Fault at Sault-au-Cochon. Note the faintly developed fault fabric.* ***E)*** *Fault breccia of the Cap-Tourmente Fault.* ***F)*** *Fault breccia with a composite matrix of crush breccia and pseudotachylyte (dark-coloured material) at Cap-Tourmente.*

DISCUSSION

The St. Lawrence and Cap-Tourmente faults share the same type of structures and fault-related rocks, suggesting that both are associated to the same event of faulting; however, at Cap-Tourmente, the St. Lawrence Fault seems to be crosscut by the Cap-Tourmente Fault (Fig. 1B). West of Cap-Tourmente, the Montmorency Falls Fault occupies the same structural position as the St. Lawrence Fault (Fig. 1B), suggesting a possible correlation of the two structures. We think that the Montmorency Falls and St. Lawrence faults result from the development of 'en échelon' faults trending parallel to the axis of the St. Lawrence rift system. As such, the Cap-Tourmente Fault more likely represents a transfer fault (Gibbs, 1984). During the extensional faulting phase of the St. Lawrence rift system, normal faults probably propagated along the entire rift zone, but their longitudinal propagation was stopped and laterally shifted along transfer faults, producing an oblique relay between two longitudinal normal faults. As common in other rift settings (e.g. Coletta et al., 1988; Ebinger, 1989; Schlische, 1993) and suggested by Lachapelle (1993) for the St. Lawrence rift system, transfer faults possibly formed along older faults or joints inherited from an older tectonic event in the pre-rift basement.

Implications for the origin of fault-related rocks in adjacent regions

In areas surrounding Québec, Lachapelle (1993) interpreted fault gouge horizons of the St. Lawrence rift system faults as the product of upper crustal reactivation of older brittle faults; however, it is suggested that the cataclastic rocks and fault gouge of the studied area are more likely the product of a single and progressive faulting event. Major fault zones of the crust commonly show of a wide variety of fault rocks representing more or less pronounced variations of pressure, temperature, strain rate, and fluid conditions. In the elastic-frictional regime (Sibson, 1977), different types of brittle fault rocks can be juxtaposed, and this commonly records changes of deformation mechanisms during progressive deformation (Magloughlin, 1992; Swanson, 1992; Snoke et al., 1998; Fabbri et al., 2000). If our interpretation is correct, it indicates that the St. Lawrence rift system is characterized by well developed and extensive series of cataclastic rocks, gouge, and associated pseudotachylyte.

In the Charlevoix area, the St. Lawrence Fault has been interpreted as a pre-impact structure, more precisely, a Proterozoic Iapetan rift fault reactivated in the Late Ordovician during late stages of the Taconian Orogeny (Rondot, 1989, 1998). Rondot (1998) described several types of fault breccia, cataclasite, and pseudotachylyte that he has attributed to the Charlevoix impact cratering. These fault rocks have been interpreted as impactite, allochthonous and autochthonous breccia, and Martini's (1991) types A and B pseudotachylyte. Type A pseudotachylyte consists of dark-coloured veins and veinlets of melted wall rocks, whereas type B pseudotachylyte (polymictic breccia dyke or "mylolisthénite" of Rondot (1971)) is greyish to olive-greenish breccia described as irregular, fault-bounded dykes of authochtonous breccia (Rondot, 1998).

In the Petite-Rivière-St-François and Cap-Tourmente areas, fault rocks related to both the St. Lawrence and Cap-Tourmente faults belong to the cohesive cataclastic series, and consist of various types of cataclasite and foliated gouge with pseudotachylyte dykes and breccia identical to Martini's type A pseudotachylyte as described by Rondot (1998) in the Charlevoix area. Fault breccia and pseudotachylyte observed along the St. Lawrence Fault at Sault-au-Cochon and at Cap-Tourmente are identical to fault rocks of the St. Lawrence Fault at Anse-au-Sac in the Charlevoix area (Lemieux et al., 2000). The segment of the St. Lawrence Fault exposed at Sault-au-Cochon lies well outside the outer limits of the Charlevoix impact crater and brittle fault rocks of this area are obviously a primary product of the St. Lawrence rift system. This raises the question of whether or not breccia and pseudotachylyte of the Charlevoix area should be entirely attributed to impact cratering. Can some of these rocks be more likely related to faulting along the St. Lawrence rift system? Type B pseudotachylyte (i.e. "mylolisthenite" of Rondot (1971, 1998)) was not observed along the St. Lawrence and the Cap-Tourmente faults during our study, which suggests that this type of fault rock is possibly the principal characteristic of impact-related structures in the Charlevoix area.

Timing constraints for the St. Lawrence rift system

There are stratigraphic (Lavoie, 1994; Lemieux et al., 2000) and magmatic (Kumarapelli, 1985) evidence for Cambrian–Ordovician growth faulting along the St. Lawrence rift system faults; however, the lack of isotopic age data and the absence of rock strata younger than Ordovician make difficult to constrain the timing of younger increments of faulting along the St. Lawrence rift system. The normal faults crosscut Upper Ordovician strata of the St. Lawrence Lowlands, hence yielding a lower age limit for fault reactivation.

In southern Quebec, there was an extensive episode of alkaline magmatism during the Cretaceous represented by the Monteregians intrusions and their dyke swarms which crosscut the St. Lawrence Lowlands and the adjacent Appalachian fold belt. The tectonic implications of this alkaline magmatism is uncertain, but Kumarapelli (1985) suggested that faults of the St. Lawrence rift were reactivated concurrently with the Cretaceous magmatic event, whereas Hasegawa (1986) viewed these structure as reactivated faults during opening of both the Iapetus (ca. 600 Ma) and Atlantic (200–150 Ma) oceans. Adams and Basham (1989), however, have considered tenuous the evidence for reactivation during the Atlantic Ocean rifting. On the basis of isotopic characteristics of fault-related mineralized calcite veins of the St. Lawrence rift system, Carignan et al. (1997) stressed that fault reactivation occurred during the Mesozoic. Preliminary results of apatite fission-track dating of basement rocks fringing the Montmorency Falls Fault near Québec suggest active

tectonism in the Late Jurassic–Early Cretaceous (Glasmacher et al., 1998), consistent with Carignan et al.'s (1997) interpretation.

From Cap-Tourmente to La Malbaie, the St. Lawrence Fault trends consistently northeast and does not show any trend reflection across the Charlevoix impact structure (Fig. 1). This suggest that impact-related faults did not significantly alter the orientation of pre-existing structures or that the reactivation of the St. Lawrence rift system and related faults are younger than the Charlevoix impact structure. It is unlikely that a major meteoritic impact, as the one inferred for the Charlevoix area (see Rondot, 1998), would not have affected the orientation of pre-existing rift faults. This suggests that the St. Lawrence Fault is more likely younger than the impact-cratering event, which is currently attributed to the Devonian. If our interpretation of crosscutting relationships is correct and if impact age constraints are accurate, it implies that reactivation of the St. Lawrence rift system should be Late Devonian or younger, most probably concurrent with the opening of the Atlantic Ocean as suggested by several authors (e.g. Hasegawa, 1986; Carignan et al., 1997; Glasmacher et al., 1998). Ongoing fission-track analysis and 40Ar/39Ar dating in metamorphic rocks from the footwall and the hanging wall of the St. Lawrence rift faults within and outside the Charlevoix impact crater will hopefully provide absolute age data for both types of structure in the near future.

CONCLUSIONS

The mapping and investigation of fault rocks of the St. Lawrence rift system indicate that it is characterized by fault textures and fabrics belonging to the elastic-frictional regime, and are typical of faulting conditions in the upper crust. Fault rocks of the cataclastic series generally coexist with fault gouge, foliated gouge, and pseudotachylyte along most parts of the rift faults. The presence of localized gouge horizons does not mark the reactivation of rift faults but rather represents a primary textural characteristic of these supracrustal faults. Northeast-trending normal faults of the St. Lawrence rift system are genetically associated with east- and northwest-trending faults that can be interpreted as transfer faults.

Our study shows that pseudotachylyte and brittle fault rocks of the cataclastic series are not restricted to the Charlevoix impact structure and also occur along the St. Lawrence rift system. This implies that the distribution and the interpretation of brittle fault rocks of the Charlevoix area should be re-examined in order to discriminate more clearly the various sets of fault rocks and structures related to the different faulting events. Structural relationships between the St. Lawrence Fault and the inferred impact structures of the Charlevoix area also suggest that the reactivation of the St. Lawrence rift system most probably succeeded the Devonian impact cratering. Available data such as the isotope signatures of fault fluids (Carignan et al., 1997) and preliminary fission-track ages from correlative structures (Glasmacher et al., 1998) suggest that fault reactivation occurred during Mesozoic rifting of the Atlantic Ocean.

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REFERENCES

Adams, J. and Basham, P.
1989: The seismicity and seismotectonics of Canada east of the Cordillera: Geoscience Canada, v. 16, p. 3–18.

Bernstein, L.
1991: The Lower Ordovician Beekmantown Group, Québec and Ontario: Ph.D. thesis, Université de Montréal, Montréal, Quebec, 330 p.

Carignan, J., Gariépy, C., and Hillaire-Marcel, C.
1997: Hydrothermal fluids during Mesozoic reactivation of the St. Lawrence rift system, Canada: C, O, Sr and Pb isotopic characterization: Chemical Geology, v. 137, p. 1–21.

Coletta, B., LeQuellec, P., Letousey, J., and Moretti, I.
1988: Longitudinal evolution of the Suez rift structure (Egypt): Tectonophysics, v. 153, p. 221–233.

Ebinger, C.J.
1989: Tectonic development of the western branch of the East African rift system: Geological Society of America, Bulletin, v. 101, p. 885–903.

Fabbri, O., Lin, A., and Tokushige, H.
2000: Coeval formation of cataclasite and pseudotachylyte in a Miocene forearc granodiorite, southern Kyushu, Japan: Journal of Structural Geology, v. 22, p. 1015–1025.

Gibbs, A.D.
1984: Structural evolution of extensional basin margins: Journal of the Geological Society of London, v. 141, p. 609–620.

Glasmacher, U., Tremblay, A., and Zentilli, M.
1998: Post-Triassic thermo-tectonic evolution of the Laurentian margin in Québec, Canada: *in* Geological Association of Canada–Mineralogical Association of Canada meeting, Québec, Abstract Volume, p. A-66.

Hasegawa, H.S.
1986: Seismotectonics in Eastern Canada, an overview with emphasis on the Charlevoix and Miramichi regions: Earthquake Notes, v. 51, p. 23–37.

Kumarapelli, P.S.
1985: Vestiges of Iapetan rifting in the craton West of the Northern Appalachians: Geoscience Canada, v. 12, p. 54–59.

Kumarapelli, P.S. and Saull, V.A.
1966: The St. Lawrence valley system: a North American equivalent of the East African rift valley system: Canadian Journal of Earth Sciences, v. 3, p. 639–658.

Lachapelle, R.
1993: La limite sud du Bouclier canadien dans la région de Québec: un phénomène de fragmentation continentale reliée à l'ouverture de l'océan Iapetus: thèse de maîtrise, Université de Québec à Montréal, Québec, 81 p.

Laurin, A.F. and Sharma, K.N.M.
1975: Région des rivières Mistassini, Péribonca, Saguenay (Grenville 1965-1967): ministère des Richesses naturelles, Québec, RG 161, 89 p.

Lavoie, D.
1994: Diachronous tectonic collapse of the Ordovician continental margin, eastern Canada: comparison between the Quebec Reentrant and St. Lawrence Promontory: Canadian Journal of Earth Sciences, v. 31, p. 1309–1319.

Lemieux, Y., Tremblay, A., and Lavoie, D.
2000: Stratigraphy and structure of the St. Lawrence Lowland in the Charlevoix area, Québec: relationships to impact cratering: Geological Survey of Canada, Current Research 2000-2D, 7 p. (online: http://www.nrcan.gc.ca/gsc/bookstore)

Magloughlin, J.F.
1992: Microstructural and chemical changes associated with cataclasis and frictional melting at shallow crustal levels: the cataclasite-pseudotachylyte connection: Tectonophysics, v. 204, p. 243–260.

Martini, J.E.
1991: The nature, distribution and genesis of the coesite and stishovite associated with the pseudotachylyte of the Vredefort Dome, South Africa: Earth and Planetary Sciences Letters, v. 103, p. 285–300.

Robertson, P.B.
1975: Zones of shock metamorphism at the Charlevoix impact structure, Québec: Geological Society of America, Bulletin, v. 86, p. 1630–1638.

Rocher, M., Tremblay, A., Nadeau, L., and Lavoie, D.
2000: Analyse structurale et tectonique de la Plate-forme du St-Laurent (Québec, Canada): résultats préliminaires: Commission géologique du Canada, Recherches en cours 2000-D12, 7 p.

Rondot, J.
1968: Nouvel impact météoritique fossile? La structure semi-circulaire de Charlevoix: Journal Canadien des Sciences de la Terre, vol. 5, p. 1305–1317.
1971: Impactite of the Charlevoix structure, Québec, Canada: Journal of Geophysical Research, v. 76, p. 5414–5423.
1989: Géologie de Charlevoix: ministère de l'Énergie et des Ressources, Québec, MB 89-21, 606 p.
1998: Les brèches d'impact météoritique de Charlevoix: ministère de l'Énergie et des Ressources, Québec, ET 97-04, 44 p.

Sabourin, R.
1973: Geology of part of the Beaupré Seigneury, Preliminary report: Department of Natural Resources, Québec, P.R. 600, 19 p.

Schlische, R.W.
1993: Anatomy and evolution of the Triassic-Jurassic continental rift system, eastern North America: Tectonics, v. 12, p. 1026–1042.

Scholz, C.H.
1990: The Mechanics of Earthquakes and Faulting: Cambridge University Press, New York, New York, 439 p.

Shaw, B.R.
1993: Strike-slip interpretation of basin-bounding faults of the St. Lawrence Lowlands Basin in the Québec city area, Canada: American Association of Petroleum Geologists, Bulletin, v. 77, p. 743–760.

Sibson, R.H.
1977: Fault rocks and fault mechanisms: Journal of the Geological Society (London), v. 133, p. 191–213.

Snoke, A.W., Tullis, J., and Todd, V.R. (ed.)
1998: Fault-related Rocks - a Photographic Atlas: Princeton Univeristy Press, Princeton, New Jersey, 617 p.

St-Julien, P. and Hubert, C.
1975: Evolution of the Taconian orogen in the Québec Appalachians: American Journal of Science, v. 275-A, p. 337–362.

Swanson, M.T.
1992: Fault structure, wear mechanism and rupture processes in pseudotachylyte generation: Tectonophysics, v. 204, p. 223–242.

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